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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

EXPERIMENTAL DETERMINATION OF HEAVE ADDED MASS AND DAMPING OF TWO-DIMENSIONAL BULBOUS CYLINDERS AT THE FREE WATER SURFACE

by

Ralph Stahl

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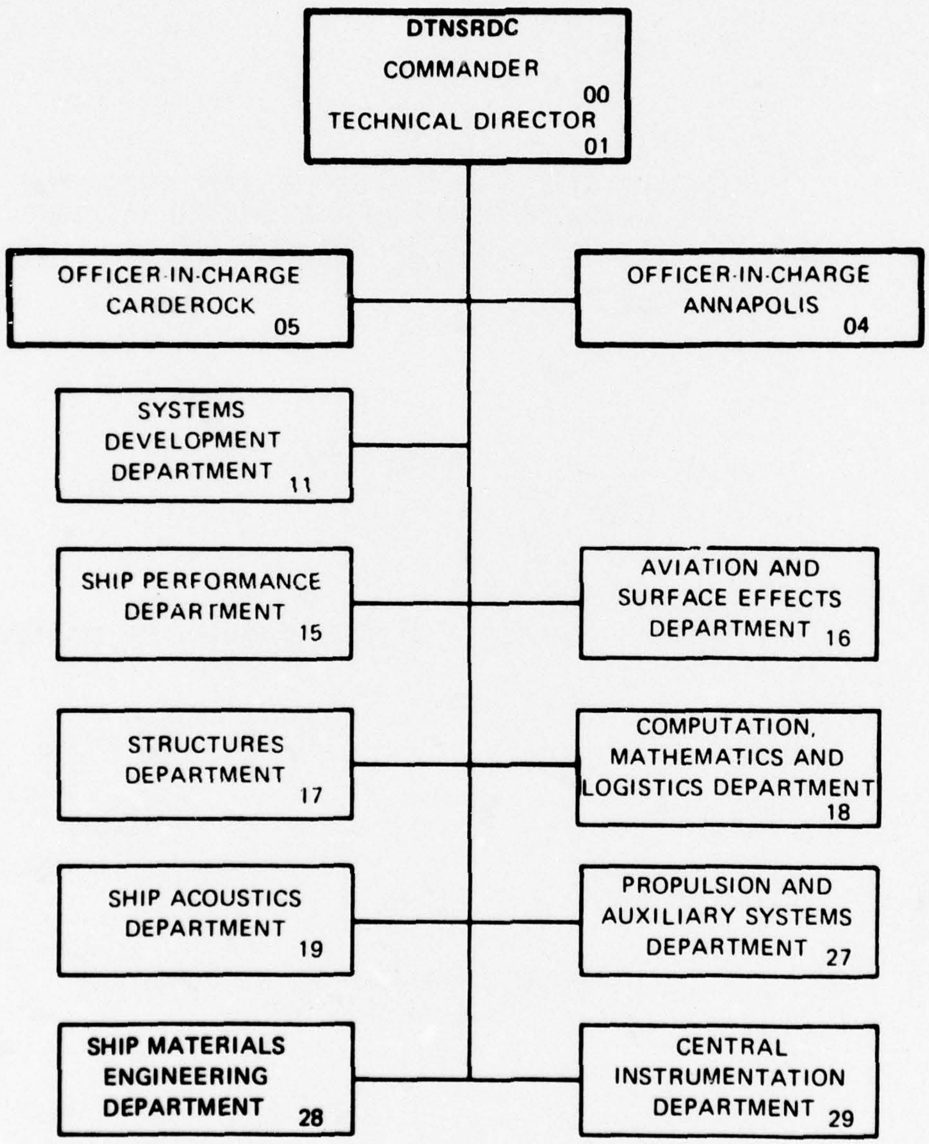

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Experimental investigations were made on several two-dimensional models to determine the hydrodynamic coefficients of heave motion. The series of cylindrical models representing small waterplane area twin hull configurations were oscillated vertically at the free water surface at various amplitudes. The results, presented in this report, indicate some significant force nonlinearity with amplitude. Both added mass and damping were appreciably affected by cross sectional hull geometry and somewhat

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by strut thickness. Draft variations least influenced the coefficients of heave motion.

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NOTATIONS

a, b, c	Coefficients in the heave equation
B	Beam of the cylinder at the waterline
F(t)	Heave forcing function
F_s	Force amplitude of the in phase component
F_c	Force amplitude of the 90 degree out of phase component
g	Gravitational acceleration
M	Displaced mass of the oscillated body
M'	Mass of the oscillated body
m	Added mass
T	Total run time
t	Time
z	Heave displacement from mean position
$\dot{z}$	Heave velocity
$\ddot{z}$	Heave acceleration
$\bar{z}$	Heave amplitude
α	Non-dimensionalized added mass coefficient
β	Phase angle between heave motion and heave forcing function
δ	Non-dimensionalized damping coefficient
ω	Radian frequency of oscillation

ABSTRACT

Experimental investigations were made on several two-dimensional models to determine the hydrodynamic coefficients of heave motion. The series of cylindrical models representing small waterplane area twin hull configurations were oscillated vertically at the free water surface at various amplitudes. The results, presented in this report, indicate some significant force nonlinearity with amplitude. Both added mass and damping were appreciably affected by cross sectional hull geometry and somewhat by strut thickness. Draft variations least influenced the coefficients of heave motion.

ADMINISTRATIVE INFORMATION

This work is part of a fundamental study of Small Waterplane Area Twin Hull (SWATH) forms authorized in Task Area ZF43422001, Element No. 62754N.

INTRODUCTION

In the process of developing analytical prediction methods for the motions of SWATH forms in waves, the Naval Ship Research and Development Center is developing a theory for determining the dynamic coefficients in the equations of motion. The theory determines the added mass and damping parameters of two-dimensional heaving bodies based on linear assumptions. The coefficients of motion of the cylindrical bodies, into which a three-dimensional hull can be divided, are then integrated over the length of the hull to obtain the desired parameters of the body. Experimental determination of the predicted added mass and damping in the heave mode for bulbous cylindrical sections is consequently very important. This is especially true for damping which is possibly dependent on nonlinear viscous effects not incorporated in the present theory. For this purpose, several bulbous cylinders consisting of completely submerged elliptical hulls with surface piercing struts were forced to oscillate harmonically in heave at several amplitudes over a given frequency range. The forces needed to impose these motions were measured and the results therefrom used to compute the added mass and damping coefficients in the equations of motion. The non-dimensionalized form of the parameters are presented in this report.

MODEL PARTICULARS

The models used in the experiment were bulbous cylindrical bodies 23.25 inches in length. With reference to Table 1, four models had elliptical hulls with surface piercing struts 1.28 inches in thickness. The ratios of major axis/minor axis of these elliptical hulls were 16.00, 4.00, 1.78, and 1.00. The fourth model had a 4.00 inch diameter hull and a surface piercing strut whose thickness could be varied with the addition or removal of panels. The three strut thickness variations were 0.65, 1.28, and 1.90 inches. The cross-sectional area of all four hulls, elliptical and circular, was constant and equal to 12.57 inches^2.

The circular cylindrical model was most representative of the various sections of SWATH IIIa, which has a circular hull cross-section and a vertical cylindrical strut having a bulbous bow and stern. The strut thickness/hull diameter ratio of SWATH IIIa sections spanning the midsection from Station 2 to Station 18 ranged from 0.0 to 0.475 with an average value of 0.319. The strut thickness of 1.28 inches for the 4-inch diameter model was derived from this ratio. This thickness may be considered representative of a SWATH IIIa strut for each hull. The strut thickness of 1.90 inches was derived using the maximum value of strut thickness/hull diameter. This maximum is located physically between Stations 8 to 12 on SWATH IIIa. The strut thickness of 0.65 inches was chosen to achieve equal increments in strut thickness.

The elliptical models were possible alternatives to the circular form. The strut thickness of 1.28 inches used for the circular hulled model was also used here.

EXPERIMENTAL SET UP AND TEST PROCEDURE

Each of the models was forced to heave sinusoidally at the free water surface. The frame utilized for connecting the models to the oscillator is shown in Figure 1. The vertically positioned plates served as "end plates" for the models and were used to preserve two-dimensional flow around the cylindrical shapes. The plates' bottom edges were both sufficiently far from the model and tapered so as to minimize their influence on the fluid flow around the two-dimensional bodies. Although the plates were stationary relative to the model they were not an integral part of the model, but instead were attached to the frame. This allowed the model to be isolated, as shown in Figure 1, with the desired result that only the static and dynamic forces exerted on the two-dimensional body were measured by the block gage.

The oscillator (MARK II) utilized for the tests harmonically oscillated the model in the heave mode via a Scotch Yoke. The frequency of oscillation was determined by the voltage input to the oscillator's motor allowing any frequency within the desired range of 0.35 to 2.30 cps. The single amplitudes of oscillation chosen for the elliptically shaped hulls were 1.0 and 2.0 inches. The amplitudes selected for the circular hull with a strut thickness of 1.28 inches and a draft of 7.40 inches were 0.5, 1.0, 1.5, and 2.0 inches. The two alternative strut thicknesses for the circular hull were tested with single amplitudes of oscillation of 1.0 and 2.0 inches whereas the two alternative drafts were tested with amplitudes of 0.5 and 1.0 inches.

The various amplitudes selected were to check linearity of the force coefficients. Variations in strut thickness and draft were to determine the added mass and damping dependency on these parameters. An alternate form for "draft" was also used. Instead of presenting the waterplane to keel distance, the distance from the waterplane to the center of the ellipse is listed in Table 1. From SWATH IIIa draft specifications, the waterplane to center of ellipse distance was determined to be 5.40 inches which was used as the mean "draft" for oscillating all three elliptical hulls and the circular hull. The alternate "drafts" for the circular hull were 3.20 and 7.25 inches.

The vertical forces exerted on the model were measured by a two-inch $\pm$ 100 lb block gauge mounted above the bodies' geometric centers (also their C.G.'s). The gauge was chosen to accommodate the high forces of the flattest elliptical hulled model. In measuring the small forces of the circular shaped hull the same block gauge was used since resolution was found to be good. The tests were conducted on Carriage 2 of the Deep Water Basin with the models' struts perpendicular to the basin walls, which allowed the generated waves to propagate away from the model in directions parallel to the basin length.

DATA EVALUATION

In analyzing the data obtained from forcing the cylindrical models to oscillate harmonically in pure heave at various amplitudes and frequencies, the following equation of motion is relevant:

$$a\ddot{z} + b\dot{z} + cz = F(t) \qquad (1)$$

where $F(t)$ = force needed to impose the prescribed heave motion

z = $\bar{z} \sin(\omega t + \beta)$ is the prescribed heave motion with amplitude $\bar{z}$, radian frequency of oscillation ω, and phase angle β between z and $F(t)$

a = the mass of the model, M, plus the added mass, m, in heave

b = heave damping coefficient

c = static heave restoring coefficient

In obtaining the acceleration and velocity coefficients in the above equations, the forcing function must first be reduced to its basic components. The equation can be written as:

$$F(t) = F_s \sin(\omega t) + F_c \cos(\omega t) \qquad (2)$$

where the term $F_s \sin(\omega t)$ is in phase and $F_c \cos(\omega t)$ is 90 degrees out of phase with the heave motion. For a nearly harmonic forcing function, $F(t)$, of period $\frac{2\pi}{\omega}$, equation (2) is the most significant portion of the Fourier series of $F(t)$. The Euler formulas of the series are:

$$F_s = \frac{2}{T}\int_0^T F(t) \sin(\omega t)\, dt \qquad (3)$$

$$F_c = \frac{2}{T}\int_0^T F(t) \cos(\omega t)\, dt \qquad (4)$$

Inserting z and its derivatives into expression (1), equating this to Equation (2) and equating the coefficients of like terms give the following two parameters:

$$a = \frac{\bar{z}c - F_s}{\bar{z}\omega^2} \tag{5}$$

$$b = \frac{F_c}{\bar{z}\omega} \tag{6}$$

The coefficient c can be obtained experimentally or by computation. Experimentally, c is obtained by statically displacing the model in heave and measuring the resultant force. Computationally, c is obtained by calculating the change in weight of the displaced water from the geometry of the model with vertical displacement. The restoring coefficients are presented in Table 1 and are used in all subsequent calculations. The coefficient was constant for each model since the struts were all cylindrical and only the struts pierced the free water surface.

The coefficients F_s and F_c were obtained electronically by analyzing the data in analog form during the test. The force signal, F(t), was multiplied by sin (ωt) and cos (ωt) utilizing a sine and cosine potentiometer, respectively. The potentiometers were linked mechanically to the oscillator in order to rotate at the frequency of oscillation and in phase with the oscillation. The products $F(t)\sin(\omega t)$ and $F(t)\cos(\omega t)$ were then integrated over an integral number of heave cycles ranging from 1 to 10. Except for a few instances, the number of cycles selected were

2 and 4. The values for F_s and F_c were obtained by multiplying the integrated terms by 2/T. Substituting F_s and F_c into Equations (5) and (6) together with the known values of $\bar{z}$, c, and ω allowed the two equations to be solved.

DISCUSSION OF RESULTS

The static coefficients (restoring coefficients) are presented in Table 1 and the experimentally determined dynamic coefficients in the equation of motion are presented in Figures 2 through 17. All dynamic parameters in the figures are non-dimensionalized according to techniques indicated by Program YFA4 in Reference 1. ~~(see Reference 2)~~ ~~and applied~~ in previous harmonic oscillation tests with two-dimensional bodies at the free water surface ~~(see Reference 3)~~. In non-dimensionalizing the added mass, damping and the frequency of oscillation, the following expressions were used:

$$\alpha = \frac{a-M'}{M} = \frac{m}{M} \tag{7}$$

$$\delta = \frac{b}{M\omega} \tag{8}$$

$$\text{non-dimensional frequency} = \frac{\omega^2 B}{2g} \tag{9}$$

where B = beam of the model at the mean waterplane position

g = the gravitational acceleration

M = mass of the water displaced by the model

M' = mass of the model

m = added mass

Generally, models are ballasted such that $M = M'$ in Equation (7) with the result that $\alpha = (a/M) - 1$ but this was not practical for the cylindrical models used here.

The order of presenting the non-dimensionalized added mass and the non-dimensionalized damping versus the non-dimensionalized frequency of oscillation for the various models is the same as that given in Table 1. That is, the elliptical hulls with the constant strut thickness are presented first with progressively decreasing ratios of major axis/minor axis ranging from 16.00 to 1.00. These are followed by the two strut variations for the circular hull and lastly by the draft variations for the circular hull with the 1.28 inch strut. The single amplitudes of oscillation 0.5, 1.0, 1.5, and 2.0 inches are each given a plotting symbol. Some data points represent an average of several runs at the same condition although the scattering of such points was not significant.

With reference to Figures 2 through 9, the results of the models having major axis/minor axis ratios of 16.00, 4.00, 1.78, and 1.00 tend to show some nonlinear effects with amplitude for added mass, particularly in the low frequency range and for damping over the whole frequency range investigated. The expected decrease in magnitude of both coefficients is seen as the submerged hull becomes more circular. Generally, the added mass shows a relatively sharp dip for low frequencies followed by an increase which tends toward constancy with increasing frequencies. The added mass for higher frequencies of oscillation becomes more linear with respect to both the amplitude of oscillation and frequency. Furthermore, as the hull becomes more circular, the slope becomes smaller and approaches zero in the high frequency range.

Damping for the four hull variations shown in Figures 6 through 9 also generally show nonlinearities in amplitude of oscillation especially for the elliptical hull whose major axis is 8.0 inches in Figure 7. The greatest variations in the velocity coefficient as with the acceleration coefficient appear in the low frequency range.

Determining the dependency of added mass on strut thickness was made with the circular hull having strut thicknesses of 0.65, 1.28, and 1.90 inches. The results are shown in Figures 10, 5, and 11, respectively. The apparent increase in the frequency range used in testing the models with increasing strut thickness is due to the non-dimensionalization method used for the frequency of oscillation. The actual range of frequencies was the same for each model. As expected, the added mass decreases with increasing strut thickness especially in the low frequency range. The slope increases from negative to positive as the strut thickness increases with α tending to approach asymptotically a value of approximately 0.55 for higher frequencies of oscillation. The corresponding dependency of damping on decreasing strut thickness is shown in Figures 12, 9, and 13. The decrease in damping with increasing strut thickness is noticeable mainly in the change from 0.65 to 1.28 inches. Some nonlinear effects with amplitude appear here also for both the acceleration and velocity coefficients, although the degree of nonlinearity was less than for the already discussed elliptical hulls.

The added mass results for the draft variations on the circular hull with strut thickness of 1.28 inches are shown in Figures 14, 5, and 15, respectively. The drafts selected were 5.20, 7.40, and 9.25 inches. Added mass in all three cases decreased with increasing frequency and tended to approach asymptotically a value of approximately 0.55 for large frequencies as was previously observed with the strut thickness variation on the same model. The coefficient can also be seen to be relatively independent with draft. The corresponding damping characteristics of the three model configurations are given in Figures 16, 9, and 17. The velocity coefficient, δ, generally decreased with increasing draft. Both dynamic coefficients, α and δ tended to show some nonlinearity with amplitude here also although to a relatively small degree.

CONCLUSIONS

Four two-dimensional models with surface piercing struts and hull cross sections ranging from an extreme ellipse to a circle were tested to determine the dynamic coefficients of heave motion. Strut thickness and draft variation in the circular cylinder hulled model were also investigated. Based on these results, the following conclusions can be made.:

1. In varying the elliptical hull to become progressively more circular, added mass was in general somewhat nonlinear in amplitude of oscillation over the range of frequencies tested whereas damping tended to be significantly nonlinear, particularly for the elliptical hull

whose major axis/minor axis = 4.0. As anticipated, both dynamic coefficients of motion decreased for an increasingly circular hull form.

2. Strut thickness variations on the circular hulled model had an appreciable effect on added mass only in the low frequency range where the magnitude changed inversely with thickness. Some nonlinearity in amplitude was present for added mass and even more so for damping throughout the investigated frequencies. Generally, damping also changed inversely with strut thickness.

3. Variations in draft on the circular hulled model did not appreciably affect added mass whereas damping generally changed inversely with draft. Nonlinearities in amplitude were evident for both added mass and damping although the degree of nonlinearity was not sufficient.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Messrs. M. Davis, J. Bonilla-Norat, and R Duerr who participated in the test program.

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TABLE 1

GEOMETRIC AND STATIC MODEL CHARACTERISTICS
AND TEST CONDITIONS FOR THE
TWO-DIMENSIONAL CYLINDRICAL SECTIONS

Elliptical Hull Geometric and Static Characteristics								Heave Oscillation Test Conditions	
Horizontal Major Axis (inches)	Vertical Minor Axis (inches)	Strut Thickness (inches)	Cylinder Length (inches)	Distance from Waterline to Center of Ellipse (Inches)	Cross-sectional Area Below Waterline (in.^{2})	Displacement (lbs)	Restoring Coefficient lbs/ft*	Single Amplitude of Oscillation (inches)	Frequency of Oscillation (cps)
16.00	1.00	1.28	23.25	5.40	18.84	15.82	12.90	1.0 & 2.0	0.35 - 2.3
8.00	2.00	1.28	"	5.40	18.20	15.28	12.90	1.0 & 2.0	0.35 - 2.3
5.34	3.00	1.28	"	5.40	17.56	14.74	12.90	1.0 & 2.0	0.35 - 2.3
4.00	4.00	1.28	"	5.40	16.92	14.20	12.90	0.5, 1.0, 1.5, & 2.0	0.35 - 2.3
"	"	0.65	"	5.40	14.78	12.41	6.55	1.0 & 2.0	0.5 - 2.1
"	"	1.90	"	5.40	19.03	15.97	19.14	1.0 & 2.0	0.5 - 2.1
"	"	1.28	"	3.20	14.10	11.84	12.90	0.5 & 1.0	0.5 - 2.1
"	"	1.28	"	7.25	19.29	16.19	12.90	0.5 & 1.0	0.5 - 2.1

*Applicable only when strut pierces the free water surface.

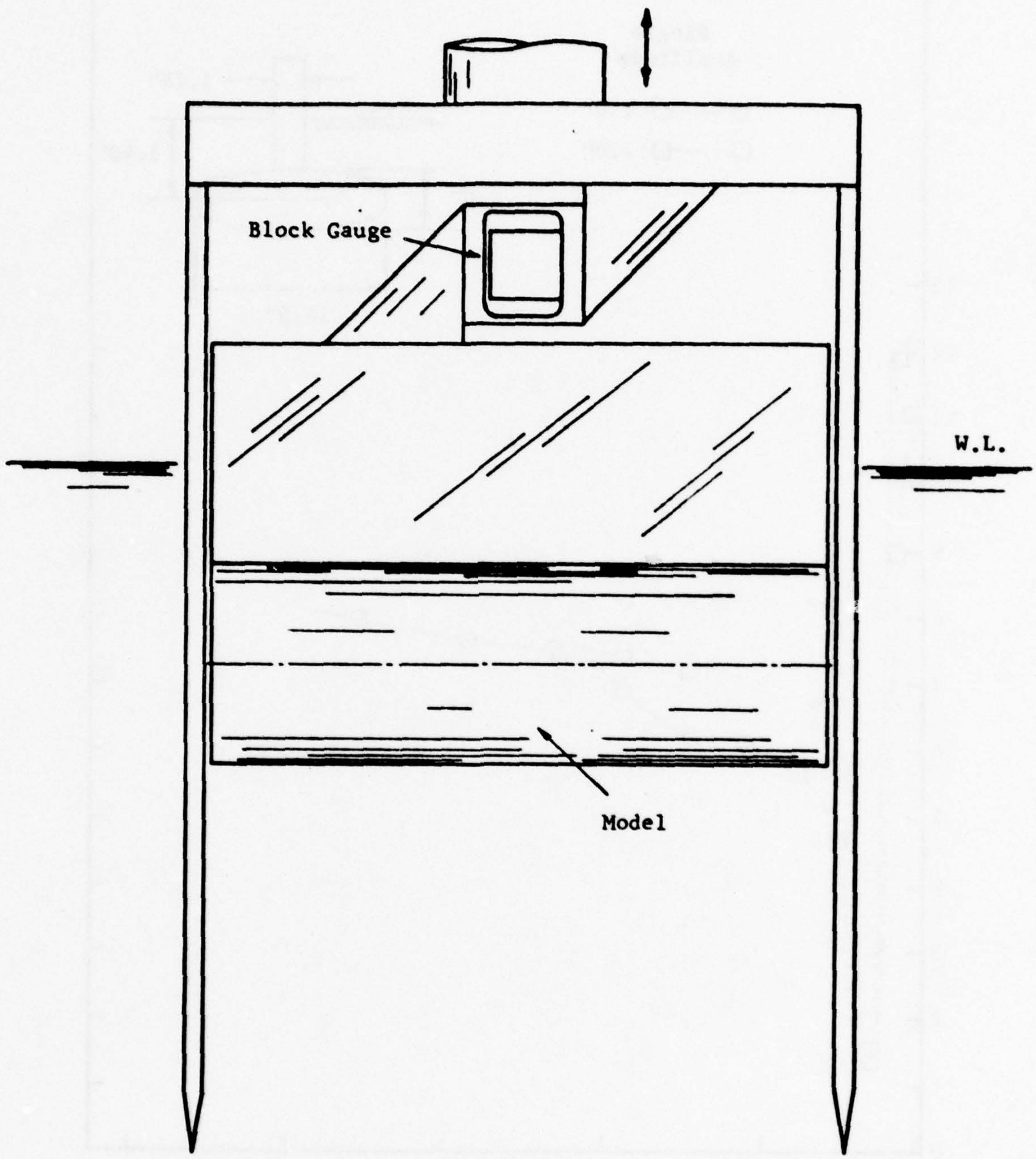

Figure 1 - Diagram of the Frame and the Mounting Technique of a Two-Dimensional Model Oscillated in Heave

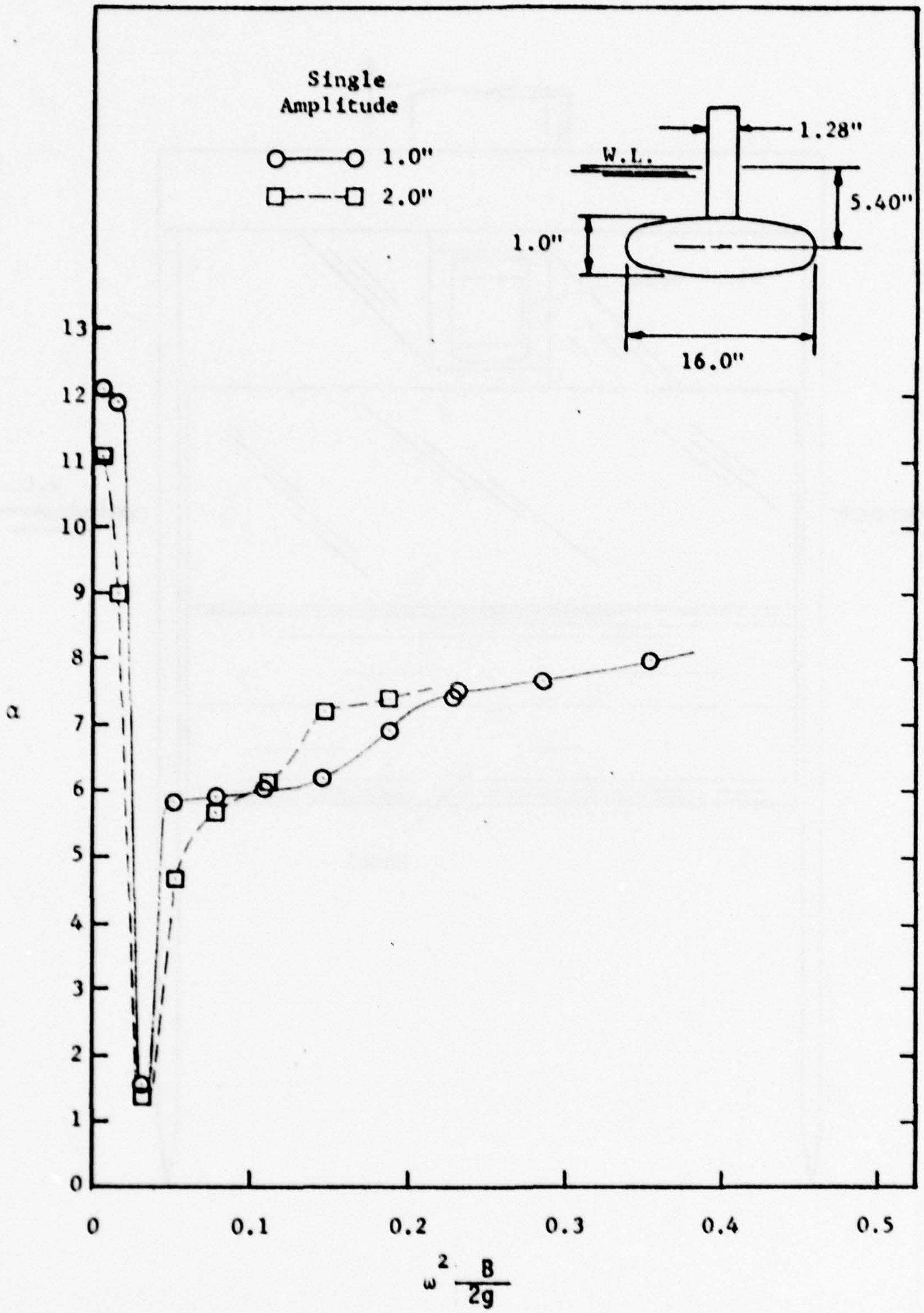

Figure 2 - Added Mass Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut - Major Axis/Minor Axis = 16.00

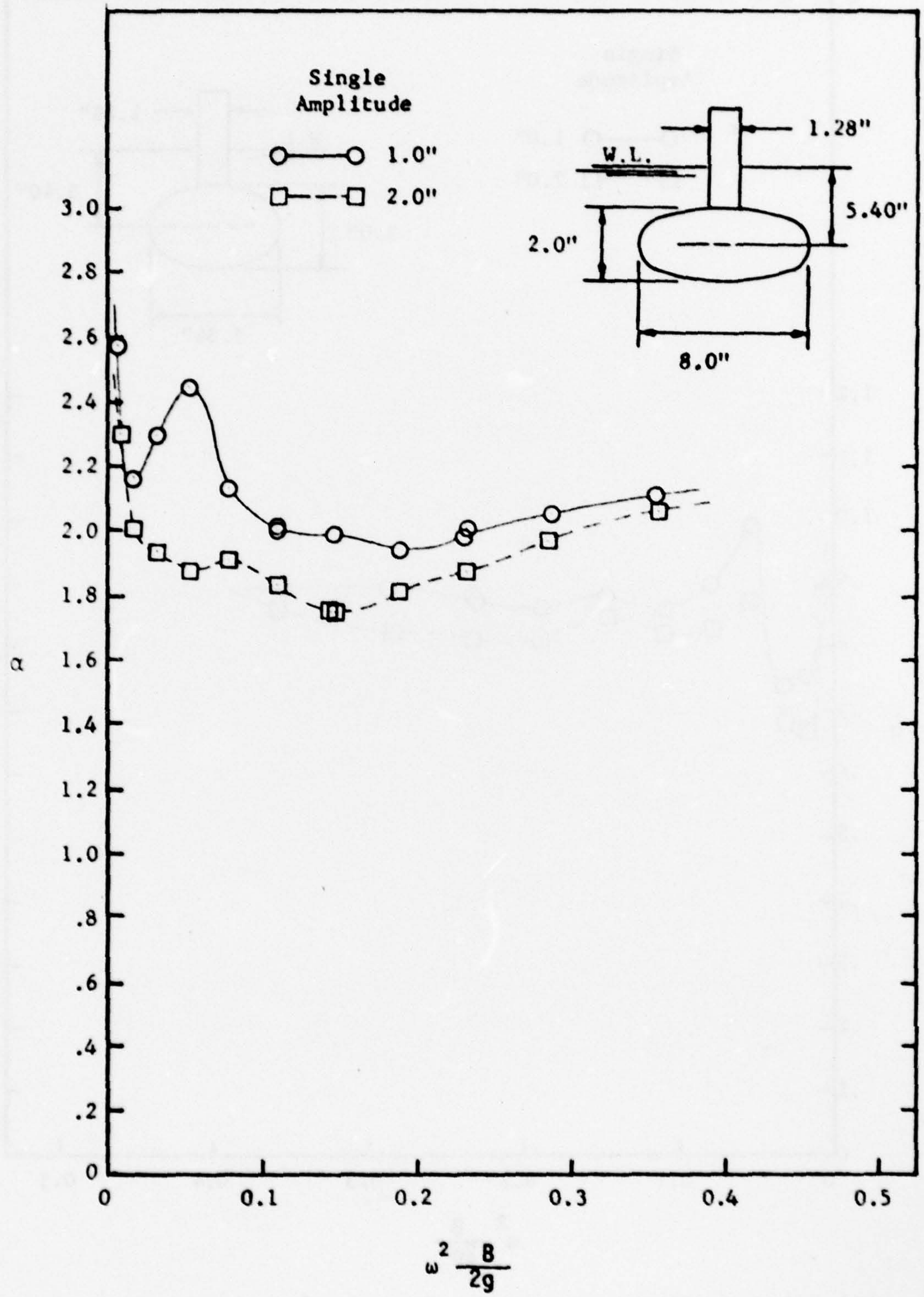

Figure 3 - Added Mass Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut - Major Axis/Minor Axis = 4.00

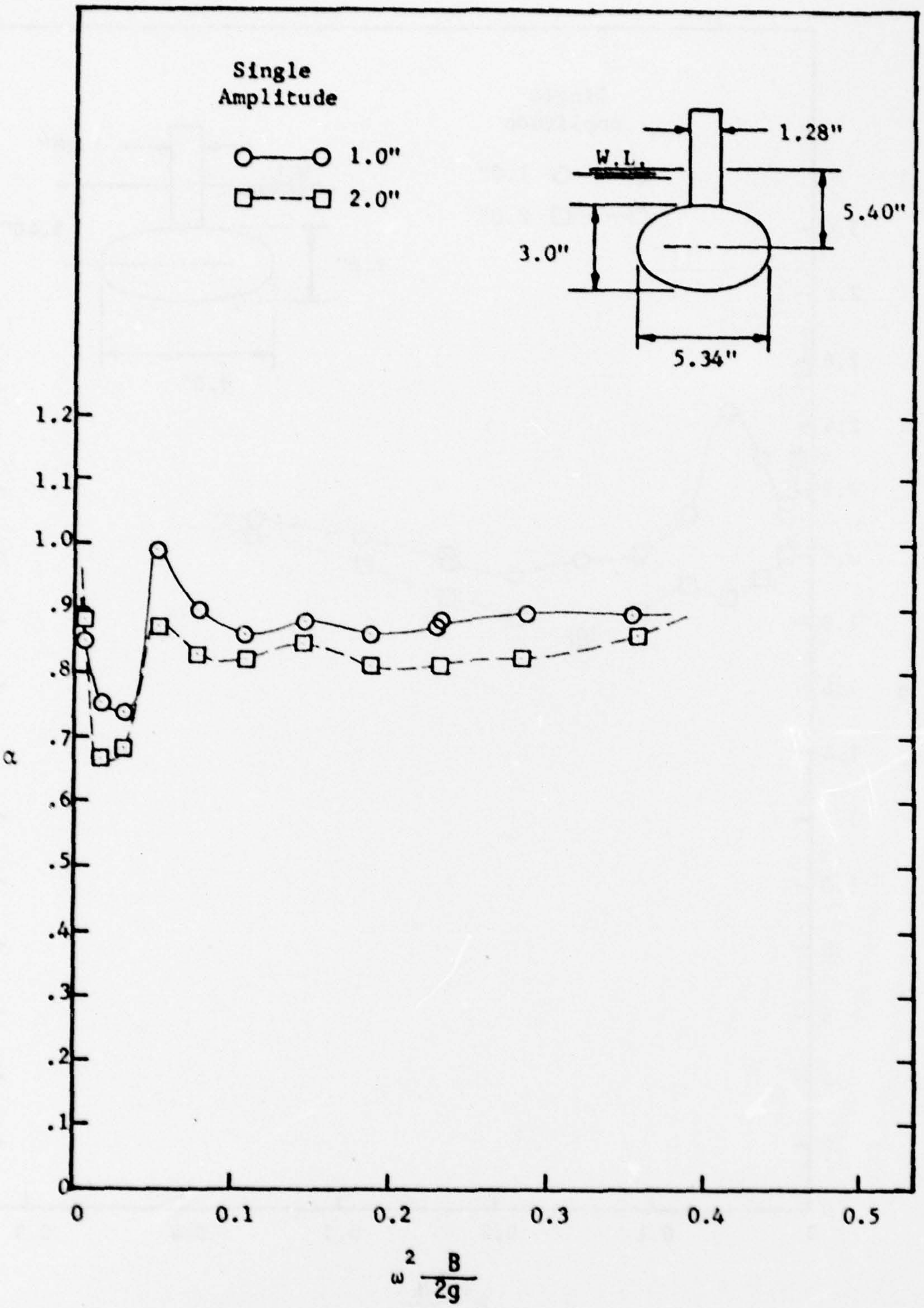

Figure 4 - Added Mass Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut - Major Axis/Minor Axis = 1.78

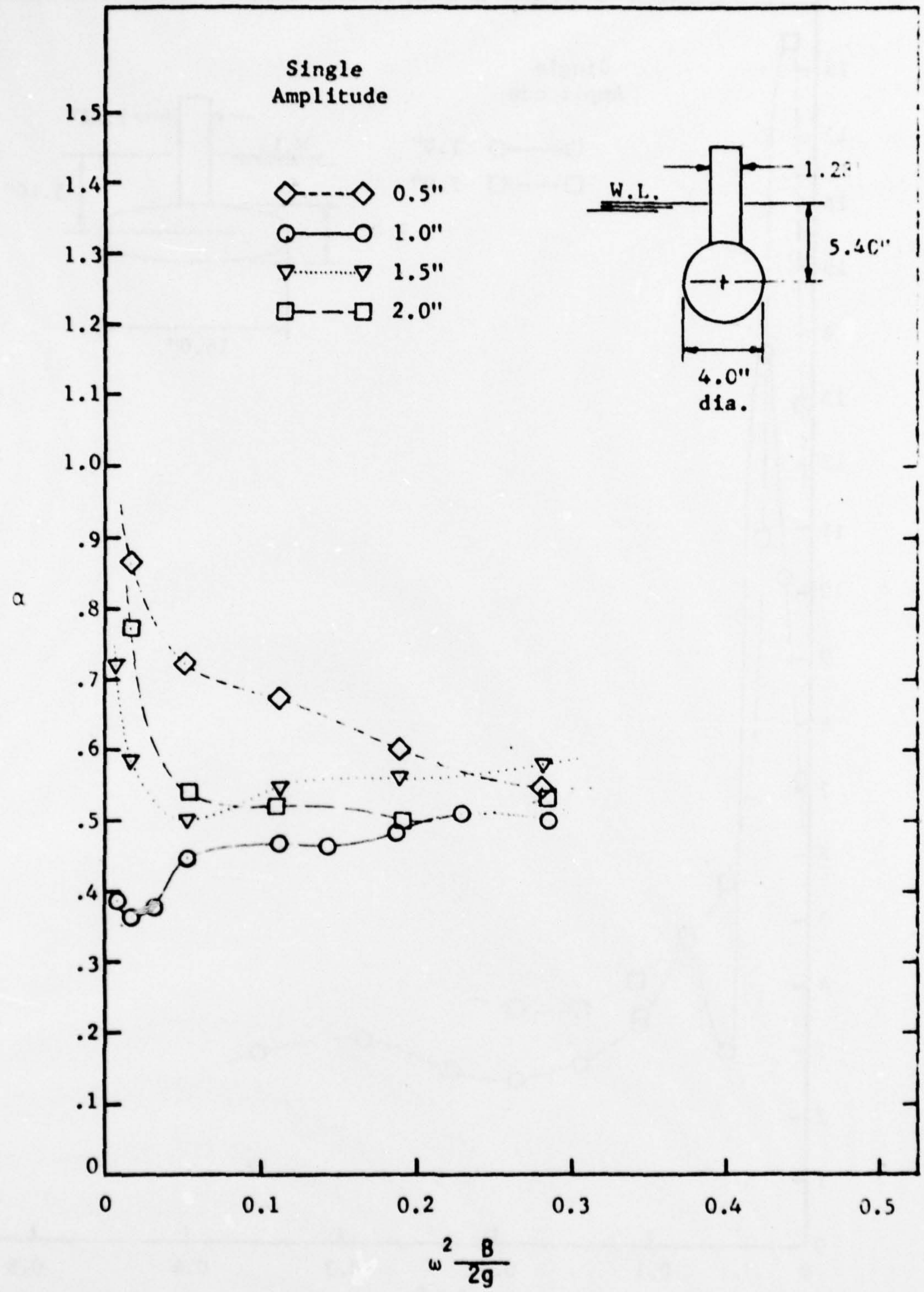

Figure 5 - Added Mass Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut - Major Axis/Minor Axis = 1.00

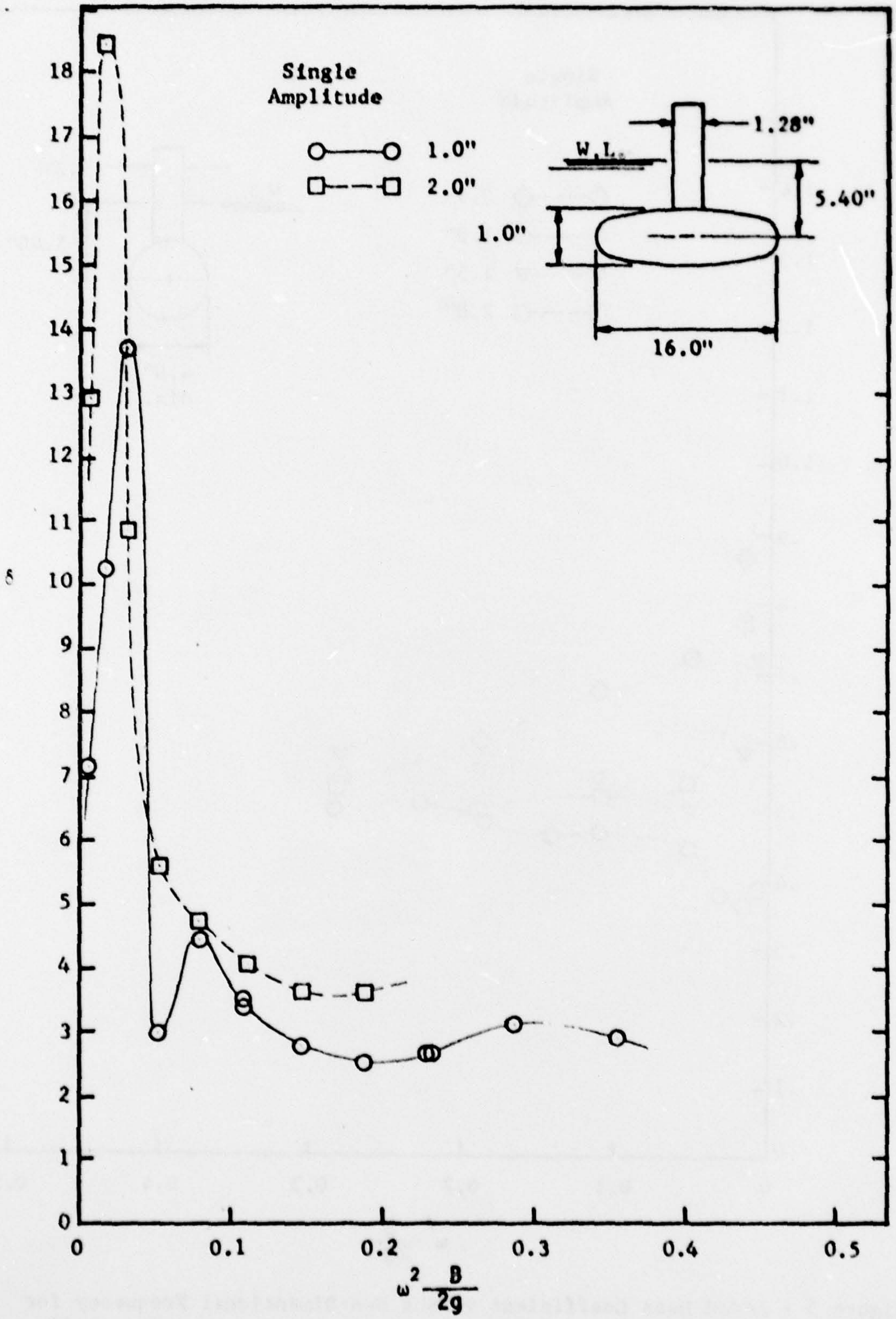

Figure 6 - Damping Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut - Major Axis/Minor Axis = 16.00

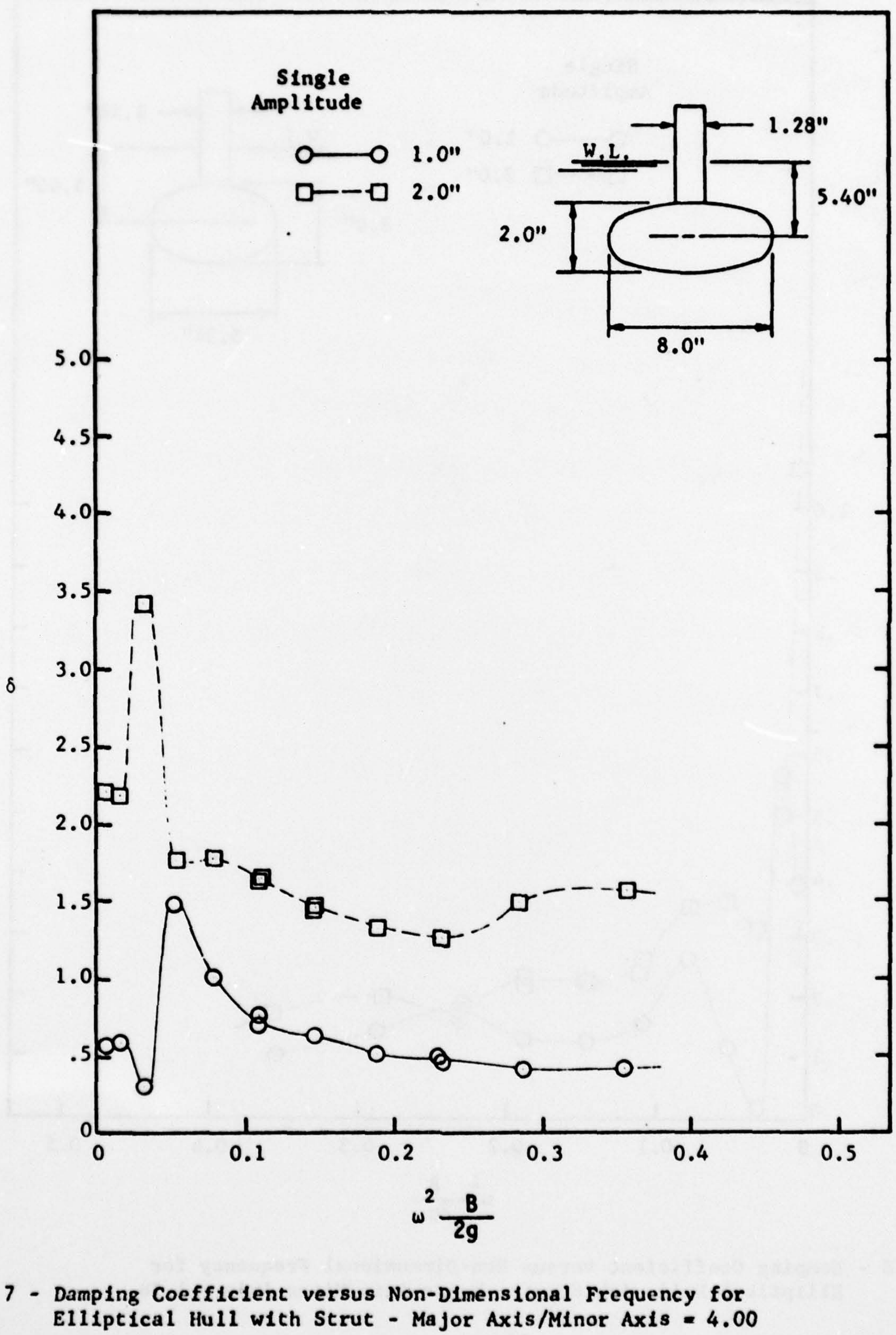

Figure 7 - Damping Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut - Major Axis/Minor Axis = 4.00

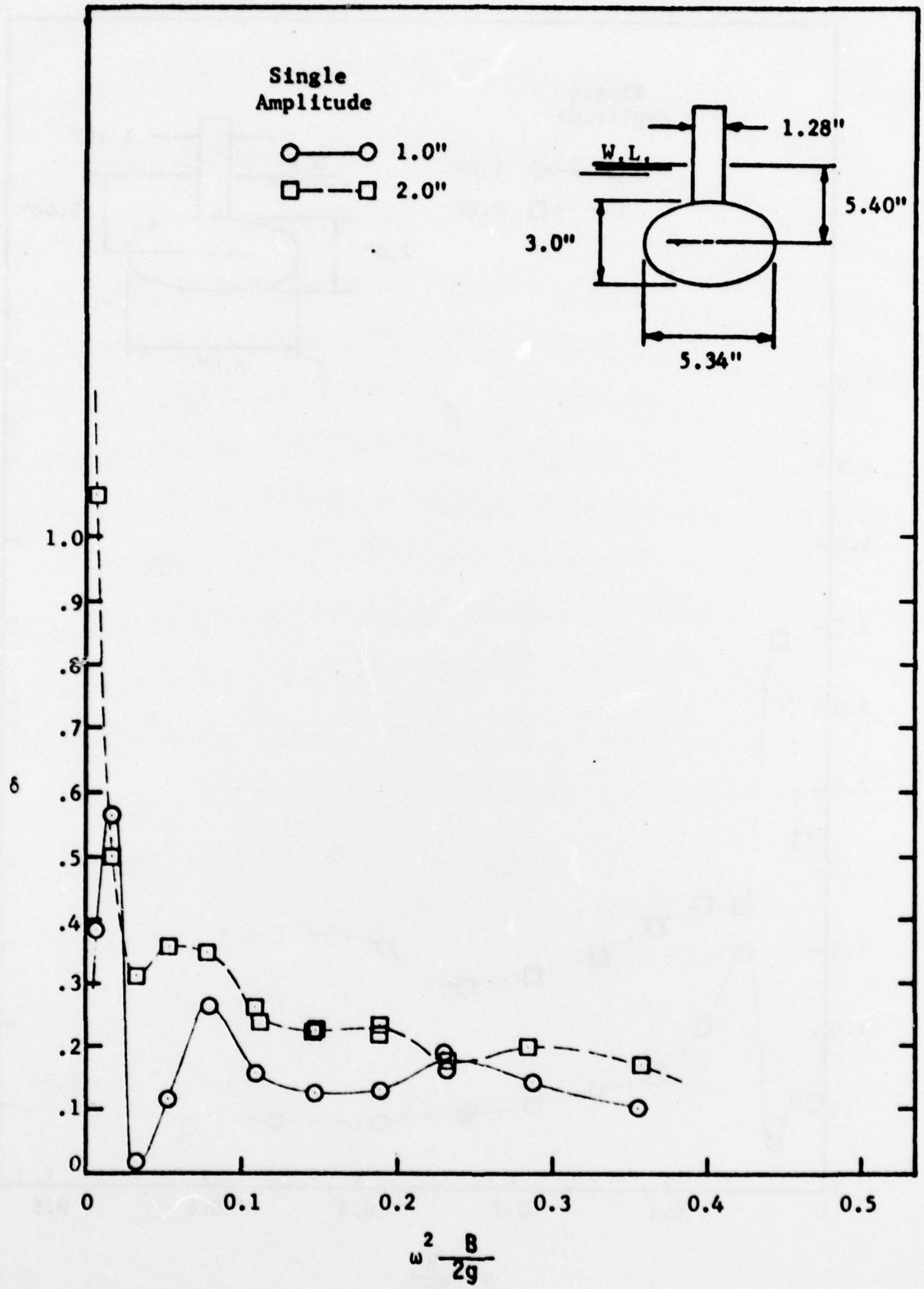

Figure 8 - Damping Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut - Major Axis/Minor Axis = 1.78

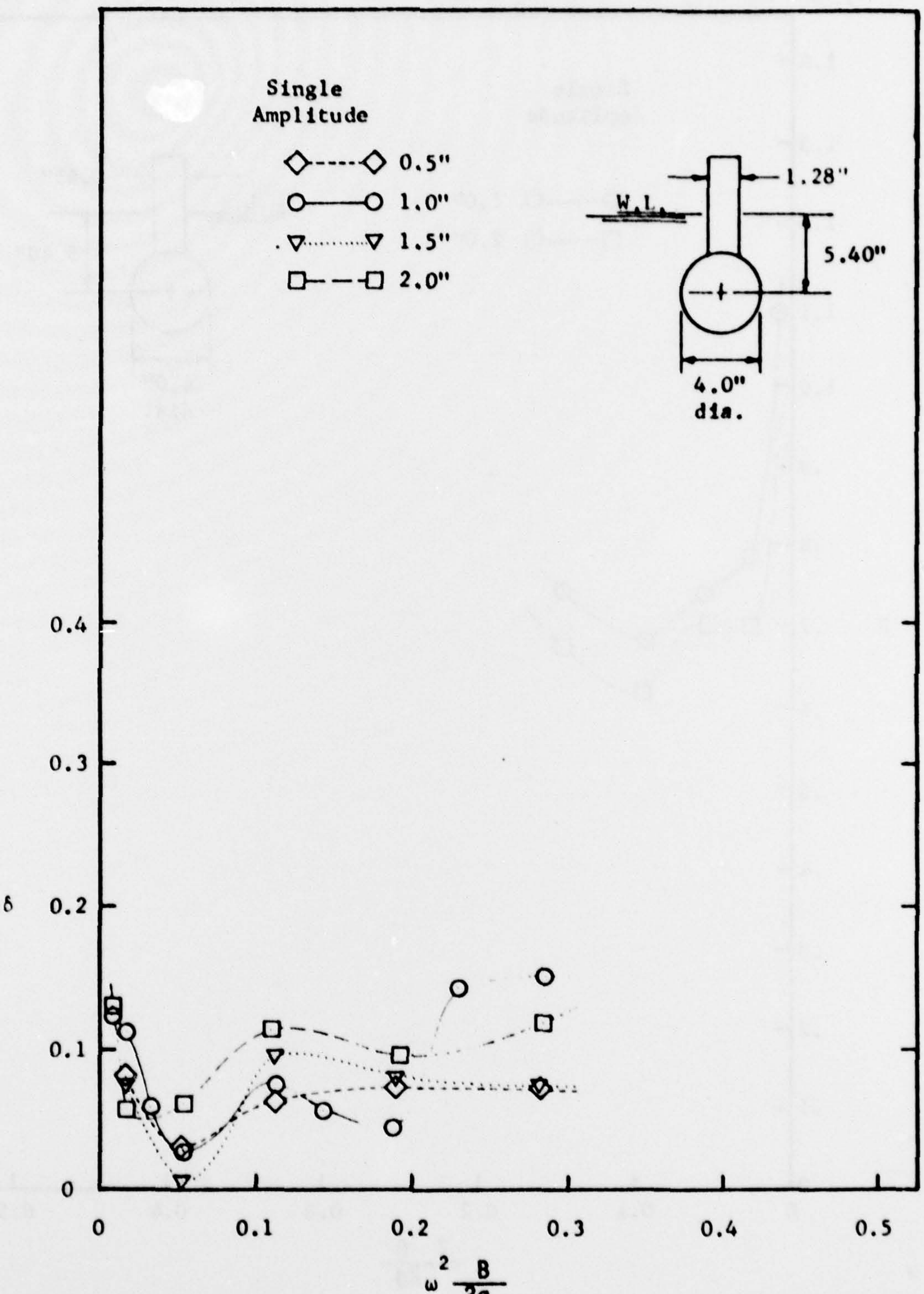

Figure 9 - Damping Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut - Major Axis/Minor Axis = 1.00

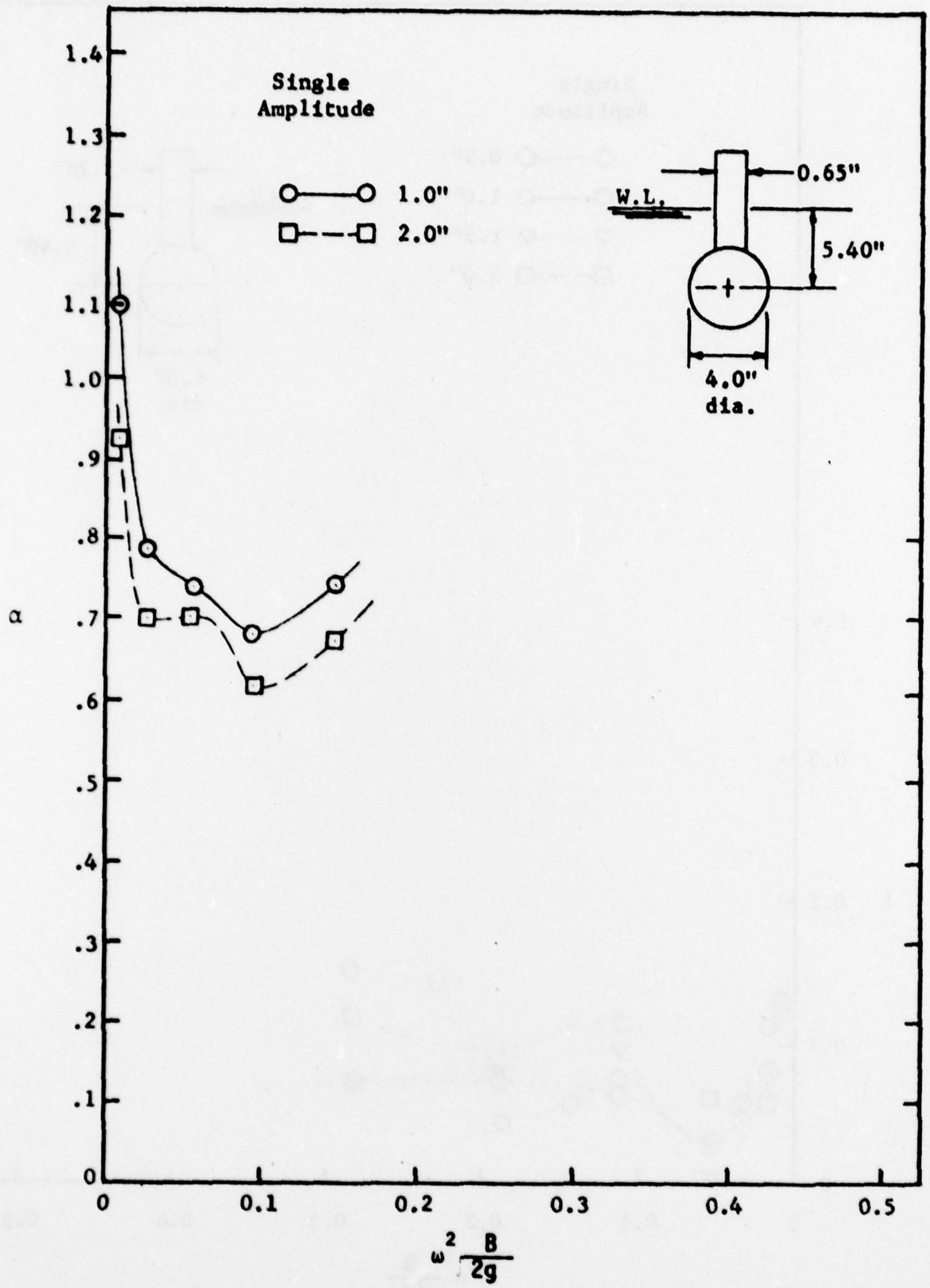

Figure 10 - Added Mass Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Alternate Strut Thickness of 0.65 inches - Major Axis/Minor Axis = 1.00

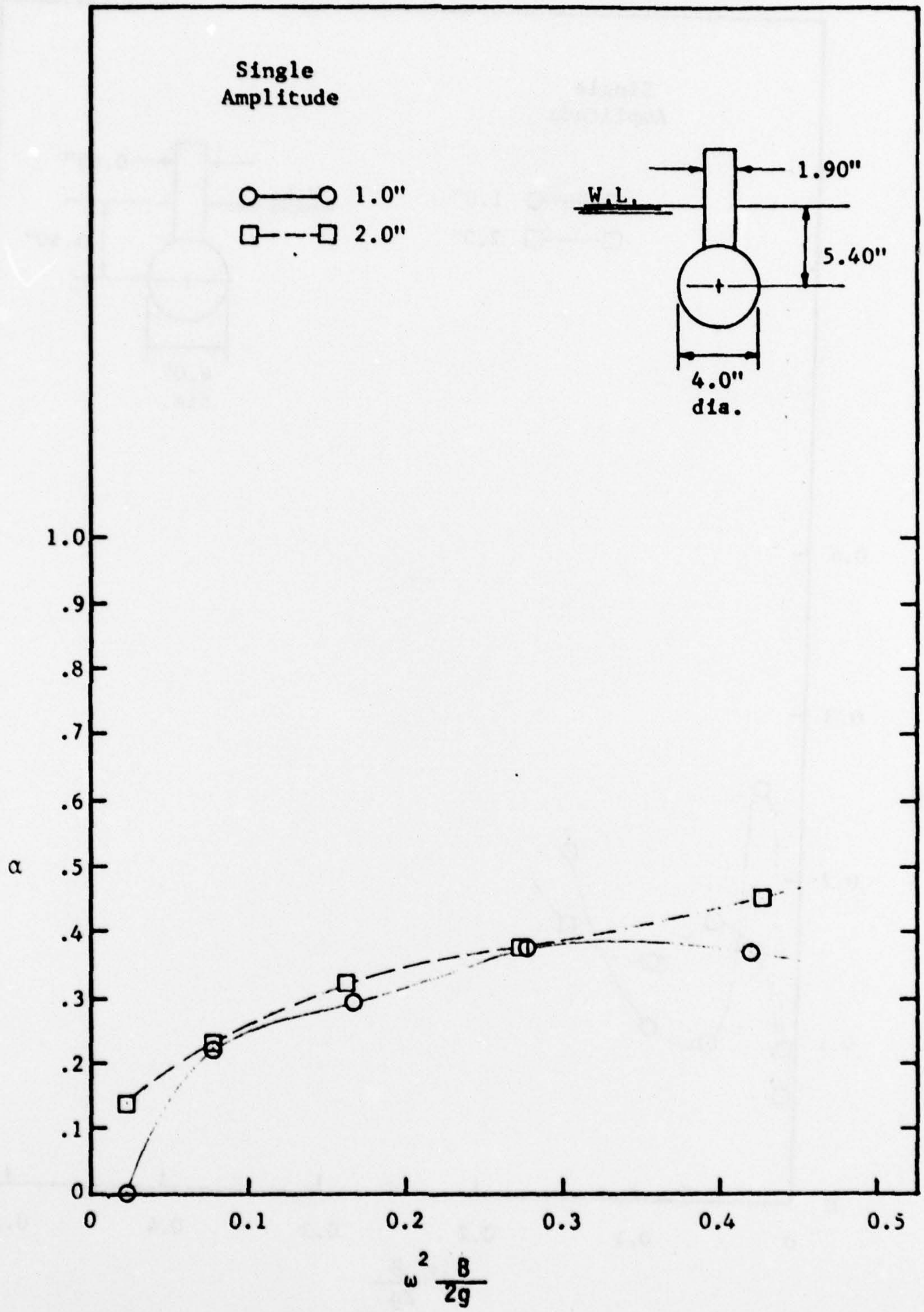

Figure 11 - Added Mass Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Alternate Strut Thickness of 1.90 inches - Major Axis/Minor Axis = 1.00

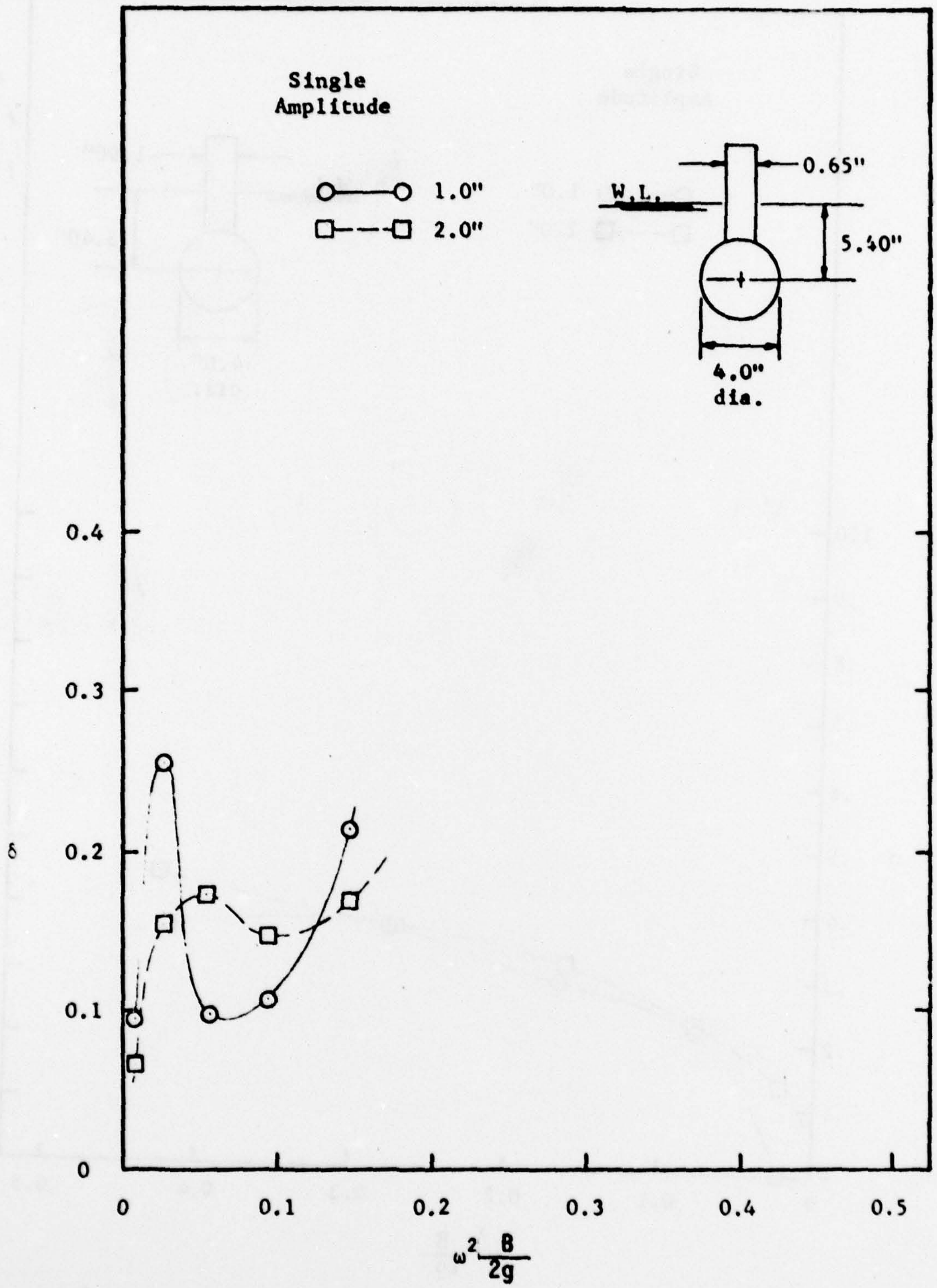

Figure 12 - Damping Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Alternate Strut Thickness of 0.65 inches - Major Axis/Minor Axis = 1.00

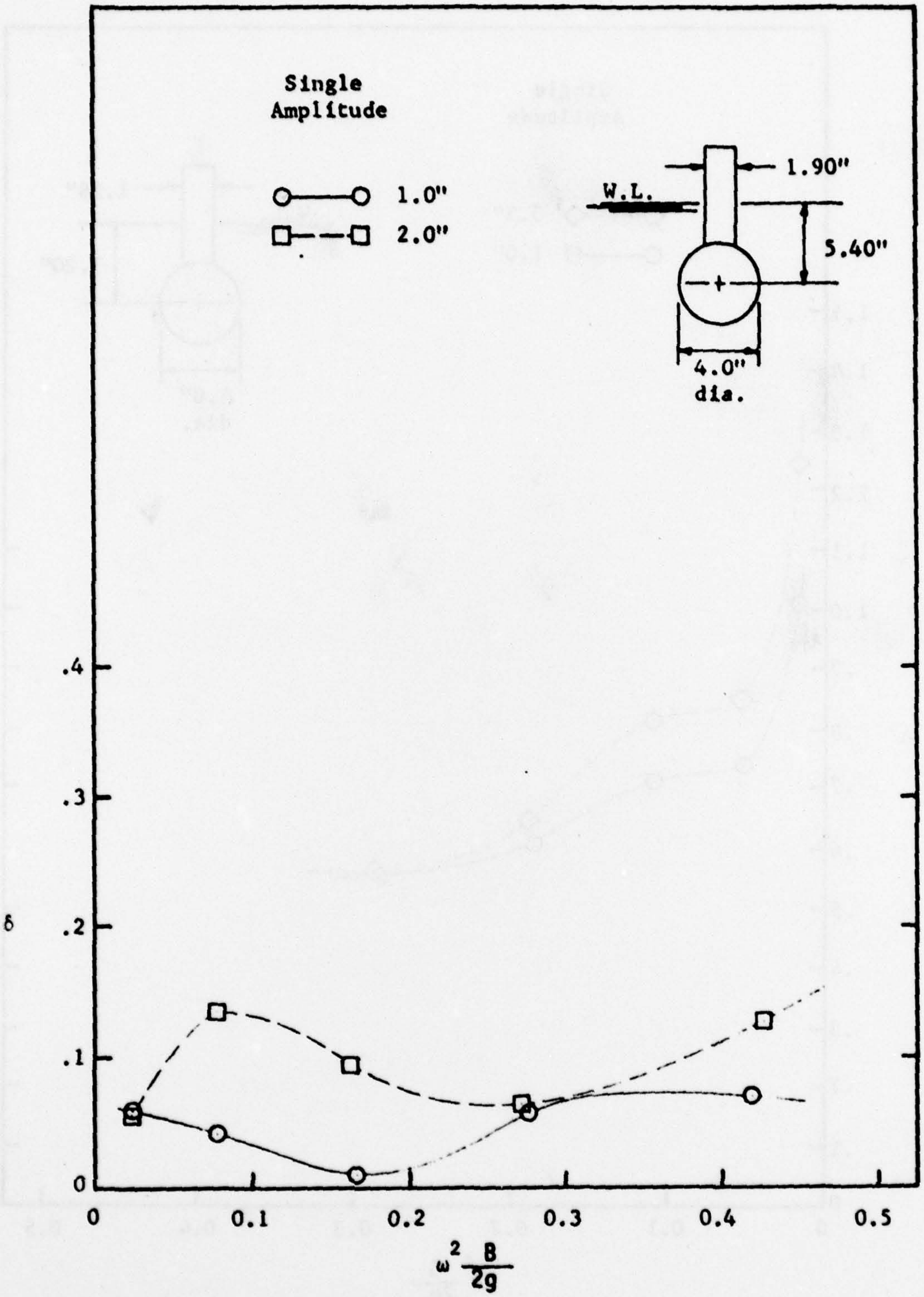

Figure 13 - Damping Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Alternate Strut Thickness of 1.90 inches - Major Axis/Minor Axis = 1.00

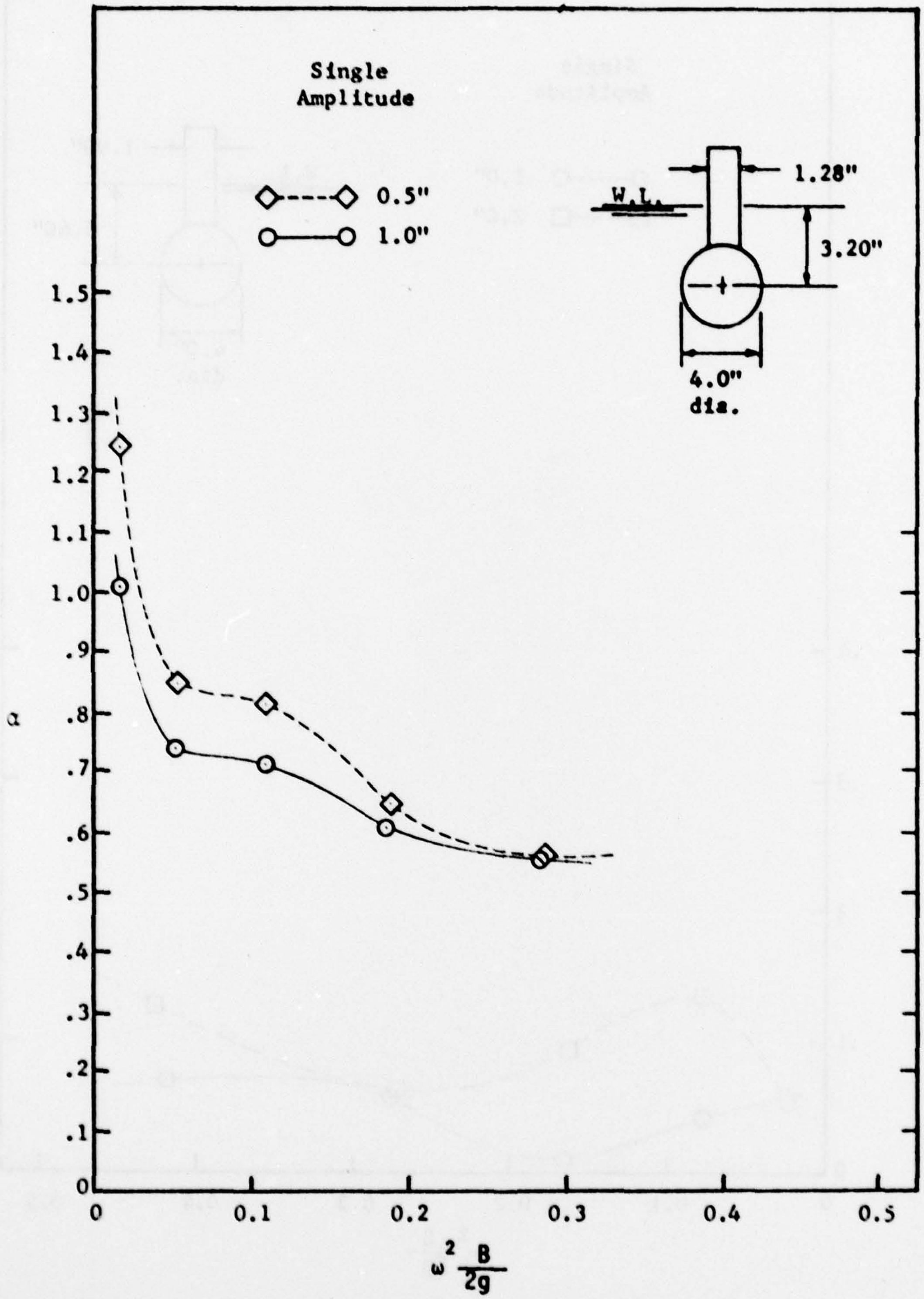

Figure 14 - Added Mass Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut and Alternate Draft of 5.20 inches - Major Axis/Minor Axis = 1.00

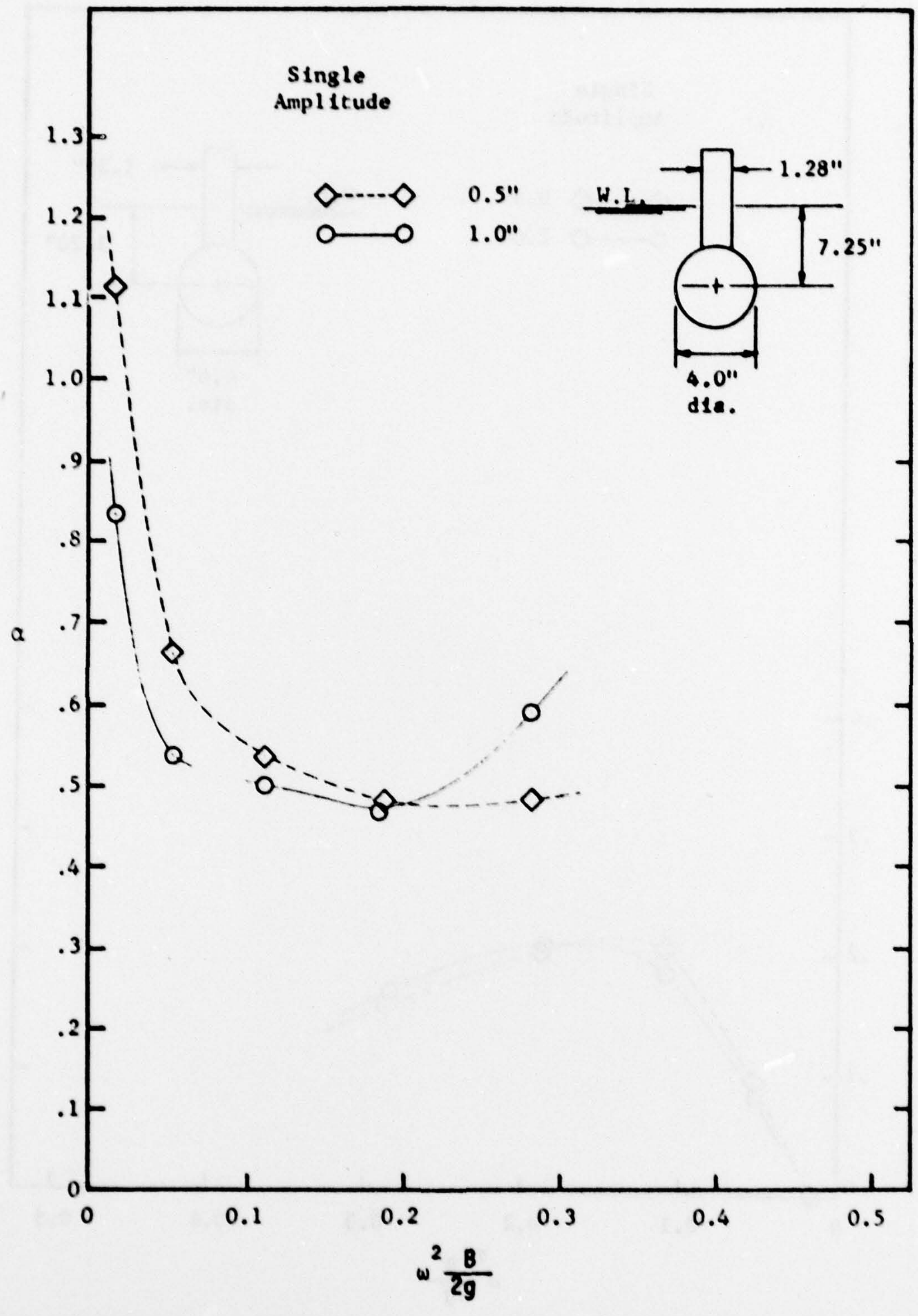

Figure 15 - Added Mass Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut and Alternate Draft of 9.25 inches - Major Axis/Minor Axis = 1.00

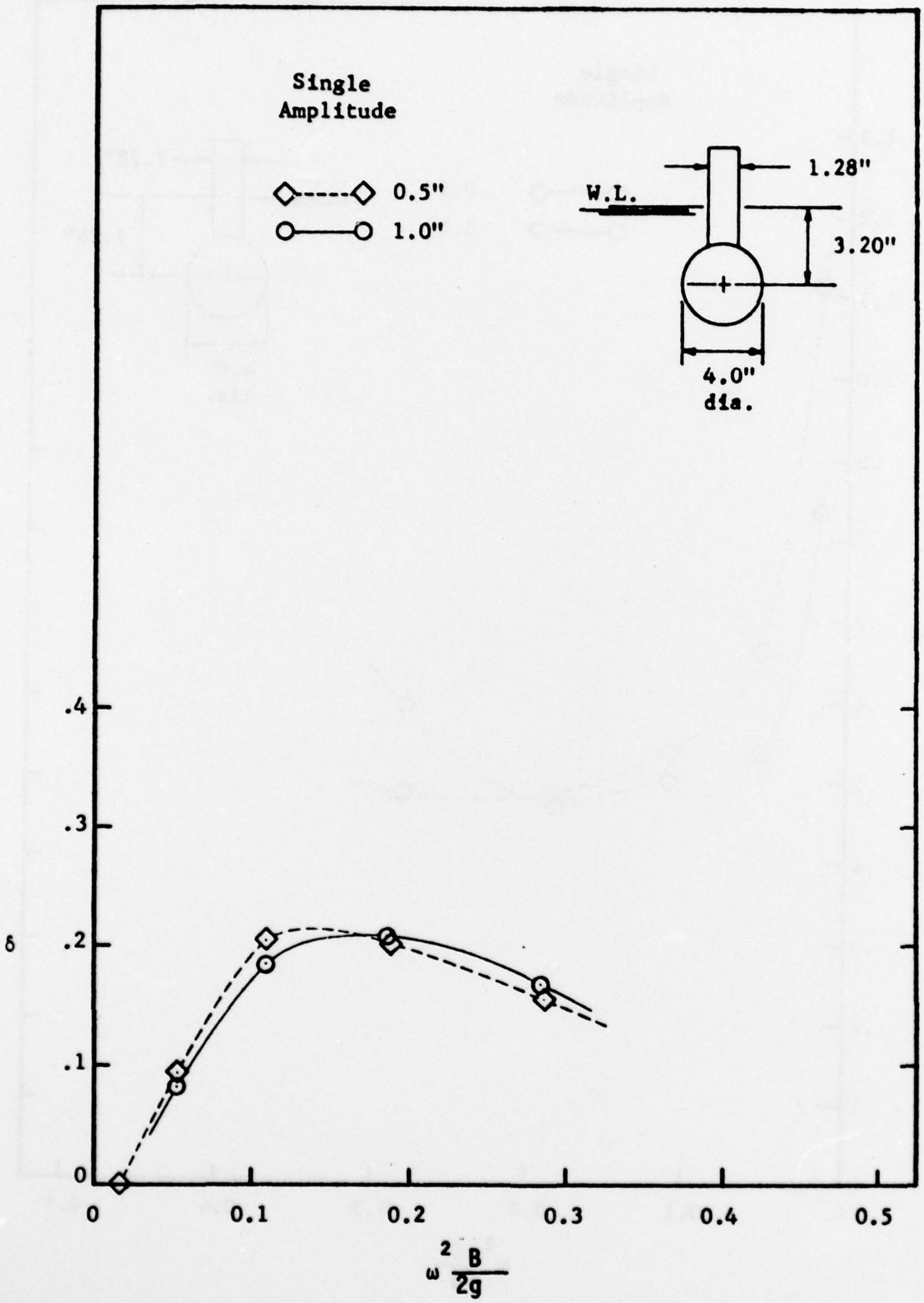

Figure 16 - Damping Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut and Alternate Draft of 5.20 inches - Major Axis/Minor Axis = 1.00

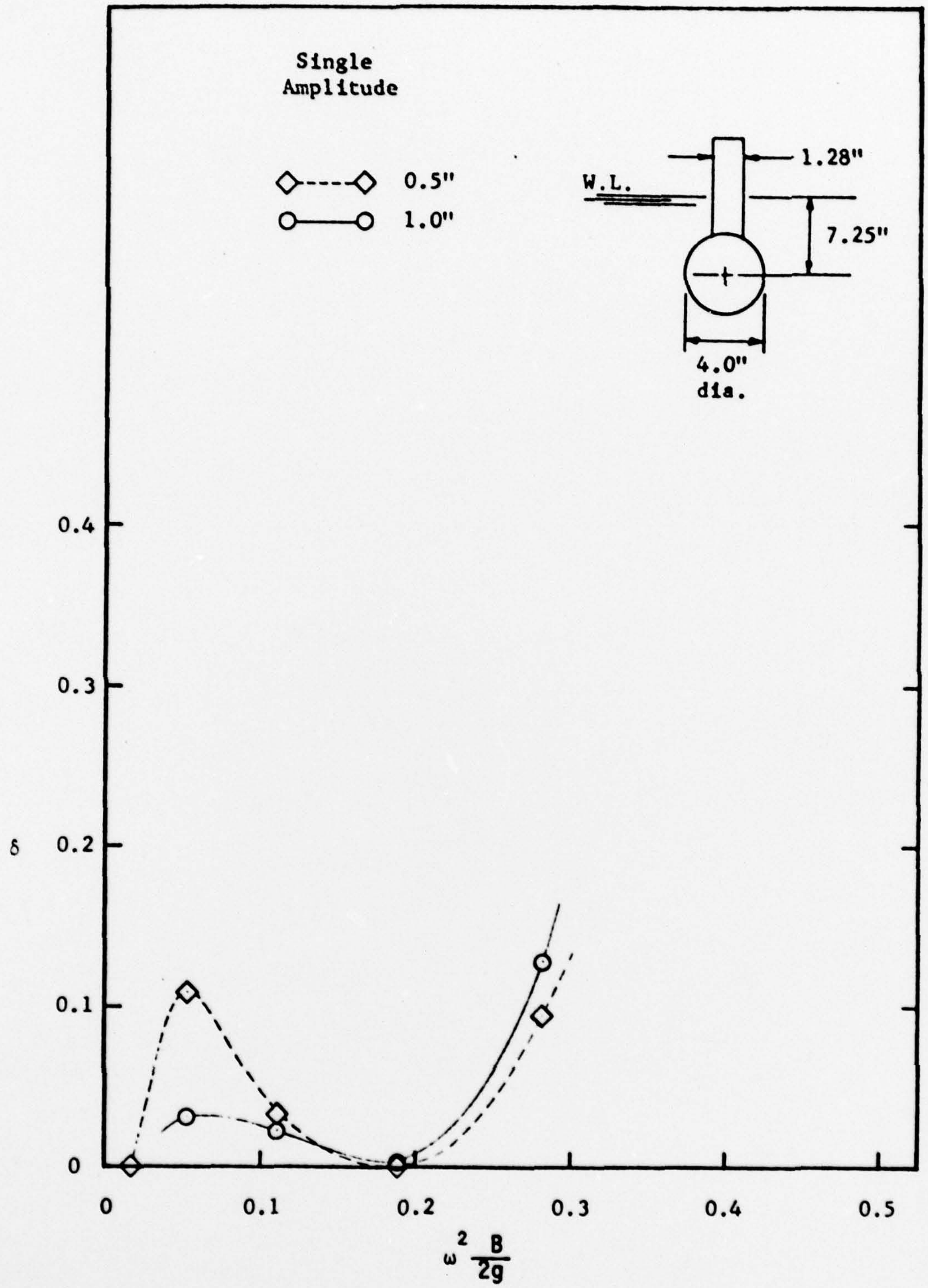

Figure 17 - Damping Coefficient versus Non-Dimensional Frequency for Elliptical Hull with Strut and Alternate Draft of 9.25 inches - Major Axis/Minor Axis = 1.00